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AIR FORCE FLIGHT DYNAMICS LABORATORY
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WRIGHT PATTERSON AIR FORCE BASE OHIO

RESULTS OF A FEASIBILITY STUDY FOR HIGH PRESSURE ELECTRON BEAM DIAGNOSTICS IN THE AFFDL HIGH TEMPERATURE FACILITY

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TECHNICAL MEMORANDUM AFFDL-TM-75-154-FXN

Research and Development Group
Experimental Engineering Branch
Aeromechanics Division
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio 45433

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FOREWORD

This Technical Memorandum describes electron beam tests made in the Air Force Flight Dynamics Laboratory High Temperature Facility as a feasibility study for high density electron beam diagnostics for nitrogen vibrational temperature measurements in the cavity of a gas dynamic laser.

The tests were undertaken at the request of the Air Force Weapons Laboratory. The experimental design and interpretation were done by S.S. Lazdinis. The optical instrumentation was set-up by R.F. Carpenter with support from Jon B. Bader and Arthur G. Stringer. The electron beam generator system was operated by Glenn W. Williams Jr. and SSgt Henry Oakes. The graphics for this report were done by MSgt Donald Rutkowski and TSgt John Lindsey, while the typing was done by Mrs. Willa Scott.

ABSTRACT

Results of an unseccessful attempt to determine the feasibility of making electron beam measurements of nitrogen vibrational temperature in hypersonic air flows at high static pressures (greater than 5 Torr) are presented. A flat plate and cylindrical blunt body were used to generate the higher pressure test gas. In the case of the flat plate, reflection of secondary electrons from the plate surface caused spurious excitation of the nitrogen molecules negating the theory underlying the interpretation of the monitored fluorescence. In the case of the solid cylinder, the generated test gas was at too high a static temperature, causing serious overlapping of the bands used in making the measurements and thus making interpretation of the data impossible. An encouraging result was that the electron beam can easily penetrate flows of 40 mm static pressure.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

Experimental determination of nitrogen vibrational temperatures in the optical cavity of state-of-the-art CO_2 Gas Dynamic Lasers (GDL's) is needed to verify theoretical predictions of laser efficiency and to study various problems affecting the optimization of GDL performance. Because nitrogen vibrational and rotational temperatures have been routinely measured in low density hypersonic facilities with the electron beam diagnostic technique, the Air Force Weapons Laboratory (AFWL) has requested the Flight Dynamics Laboratory (AFFDL) to study the feasibility of applying the electron beam method to measure nitrogen vibrational temperatures in the cavity of an actual, working gasdynamic laser such as that in operation at NASA Ames.

Because electron beam measurements of nitrogen vibrational temperature have only been made in the fairly low pressure regime up to ~5 Torr, while the GDL environment is characterized by pressures to the 50 Torr range, the specific purpose of this effort was to determine the possibility of extending the technique to the previously unexplored pressure range from 5 to 40 Torr. Currently, nitrogen vibrational temperatures obtained with the electron beam technique, at pressures below 0.5 Torr, have accuracies between 10 and 15%, the limitation to higher accuracy being caused by the present day values of the Franck-Condon Factors used to reduce the spectroscopic data.

This report presents the results of an attempt by AFFDL personnel to extend the pressure range of electron beam measurements of nitrogen vibrational temperature. The effort was made in the Flight Dynamics Laboratory's

High Temperature Facility. Although the results were inconclusive, it is felt that the information obtained will be valuable in further delineating the use of electron-beam diagnostics.

SECTION II

BACKGROUND INFORMATION

To better understand the rationale for making these tests, it is necessary to review the status of the electron-beam developmental effort at the AFFDL at the time this particular investigation was initiated in January 1975.

The R & D Group of the Flight Mechanics Division has, over a number of years, greatly extended the applicability of the electron-beam diagnostic technique from the status originally introduced by Muntz[1] as a low pressure limited tool for the measurement of nitrogen rotational temperature. Under numerous contracts and extensive in-house efforts extending over a decade, both operating voltages and currents of the electron beam generator have increased, allowing the measurement of thermochemical properties of species other than nitrogen. To date, the beam has been used to measure the following gas properties in AFFDL arc-tunnel flows: N and N_2 number densities, N_2 vibrational and rotational temperatures, O_2 and O number densities, O_2 vibrational temperature, and NO concentrations and vibrational temperature. The results of these measurements have provided valuable insight in delineating the degree and forms of thermochemical nonequilibrium in high-enthalpy, low density arc-tunnel flows.

As a continuing laboratory effort, at the time of initiation of this study, AFFDL had a contract with the Ohio State University to determine upper pressure limits for the technique for making oxygen, nitric oxide, and nitrogen vibrational temperature measurements. Preliminary results

obtained by the contractor showed that the R-branches of the vibrational bands of the 1st Negative System of N_2^+, which are commonly used in making nitrogen vibrational temperature measurements, are overlapped by bands of the 2nd Positive System of N_2. Under static conditions and at pressures above 4mm, the effects of overlapping of the two band systems could not be separated. (The total intensity of the two overlapped bands result in total integrated intensity ratios which are too high, and thus are not characteristic of the nitrogen vibrational temperature). The immediate consequence of this result was that the integrated intensities of these bands could not be used. On the basis of this information, it was concluded that the only possibility of making nitrogen vibrational temperature measurements was to use the (0,1) and (1,2) band heads (i.e., P-branches) since they are not overlapped by the 2nd Positive System. In the past, both the peak intensities and areas of the two band heads had been used successfully to make nitrogen vibrational temperature measurements in low density flows such as produced in the Flight Dynamics Laboratory's 2-ft Electro-Gasdynamics Facility (EGF). Thus there was some optimism that these two band heads might also be usable at higher pressures.

To settle these questions, the electron beam technique had to be applied in a gas which could provide a high vibrational temperature, a low rotational temperature, and most importantly, a pressure between 5 and 40 Torr. (The nitrogen vibrational temperature in the Ames CO_2/GDL laser cavity running in a non-lasing mode is given as 1300° to 1600°K. The desired measurement accuracy is approximately ±50°K.) Because the contractor's research schedule had already programmed these investigations outside the short time frame desired by AFWL, it was decided to attempt

this same work in-house, with the view of meeting a requested June 75 deadline. The only facility at the AFFDL available for entry at the time of these tests, and which could possibly generate a test gas which could meet the experimental boundary conditions on temperature and pressure, was the High Temperature Hypersonic Facility (HTF). However, it could not meet all three constraints (low T_R, high T_V, and a P between 5 and 40 Torr) simultaneously. Although it could generate the proper temperatures, it could not provide the desired pressures in the free stream with its standard nozzle configuration.

A simple and readily available solution to generate the higher pressures was recommended to the R & D Group. It consisted of shocking the free stream gas to obtain the desired pressure by using a flat plate, set at different angles of attack to the Mach 10 flow of the HTF. By tilting the plate at various angles the pressure could be varied in definite increments, from the low values at which the electron beam technique gives known results to the higher unexplored values of interest. Although this scheme seemed attractive from the standpoints of timeliness and fluid-mechanics, it was not clearly evident that the desired test conditions could be reached. Other studies with similar flat plate configurations had shown the existence of serious problems in interpreting the spectrographic data. It was found that wrong results were produced by secondary electron excitation of the test gas. (The secondaries are low energy electrons generated by reflection of the primary beam electrons from the plate.) It has been established that secondary excitation violates the assumption that the electrons produce excitation according to the optical selection rules, i.e., the Franck-Condon principle, upon which the inter-

pretation of the electron beam fluorescence is based. The result is that the spectral information cannot be related to a rotational or vibrational temperature. A more desirable approach, free of this problem,would have been to shoot the electron beam through the back-side of the plate. However, this was not feasible in the time frame desired because the electron beam generator would have had to be tilted at a different angle corresponding to each change in angle of attack of the plate. Much machine time would gave been needed to modify the existing facility set-up to produce this capability.

Because this study was only preliminary in nature, and was the only possible way of obtaining the required answers in a short time, it was decided to proceed with the flat plate model in the HTF. A better procedure for generating the desired test gas conditions would have been to use a nozzle of smaller area ratio to produce the test stream. However, this approach would also have demanded significant facility modification and could not be completed in a short time.

SECTION III

ANALYSIS

Briefly, the electron-beam technique consists in passing a thin beam of high energy electrons (~30kv) through a test gas and spectroscopically examining the resulting radiation. The intensities of individual rotational lines and vibrational bands can be related to species concentrations while the total radiation intensity can be used to derive the overall gas density. The relative intensities of individual rotational lines within a vibrational band can be used to determine a species rotational temperature which, because of the fast equilibration rate between rotational and translational degrees of freedom in most gas systems, can give a direct reading of the gas static temperature. The relative intensities of pairs of vibrational bands can be used to derive vibrational temperatures of diatomic species. Full details of the technique can be found in Refs. 1 to 4.

Nitrogen vibrational temperatures can be experimentally obtained by measuring the intensities of various vibrational bands in the 1st Negative System of N_2^+. In the usual case, the (0,1) and (1,2) total band, band head, or band head peak intensities are determined. The intensities are ratioed and are then related to theoretically predicted values which are calculated as a function of rotational and vibrational temperature. Figure 1 reproduces typical working curves showing the behavior of calculated total band intensity ratios of the (0,1) to (1,2) bands as a function of vibrational and rotational temperature.[5] As can be seen, the sensitivity of the measurements is not uniform but decreases at both low vibrational

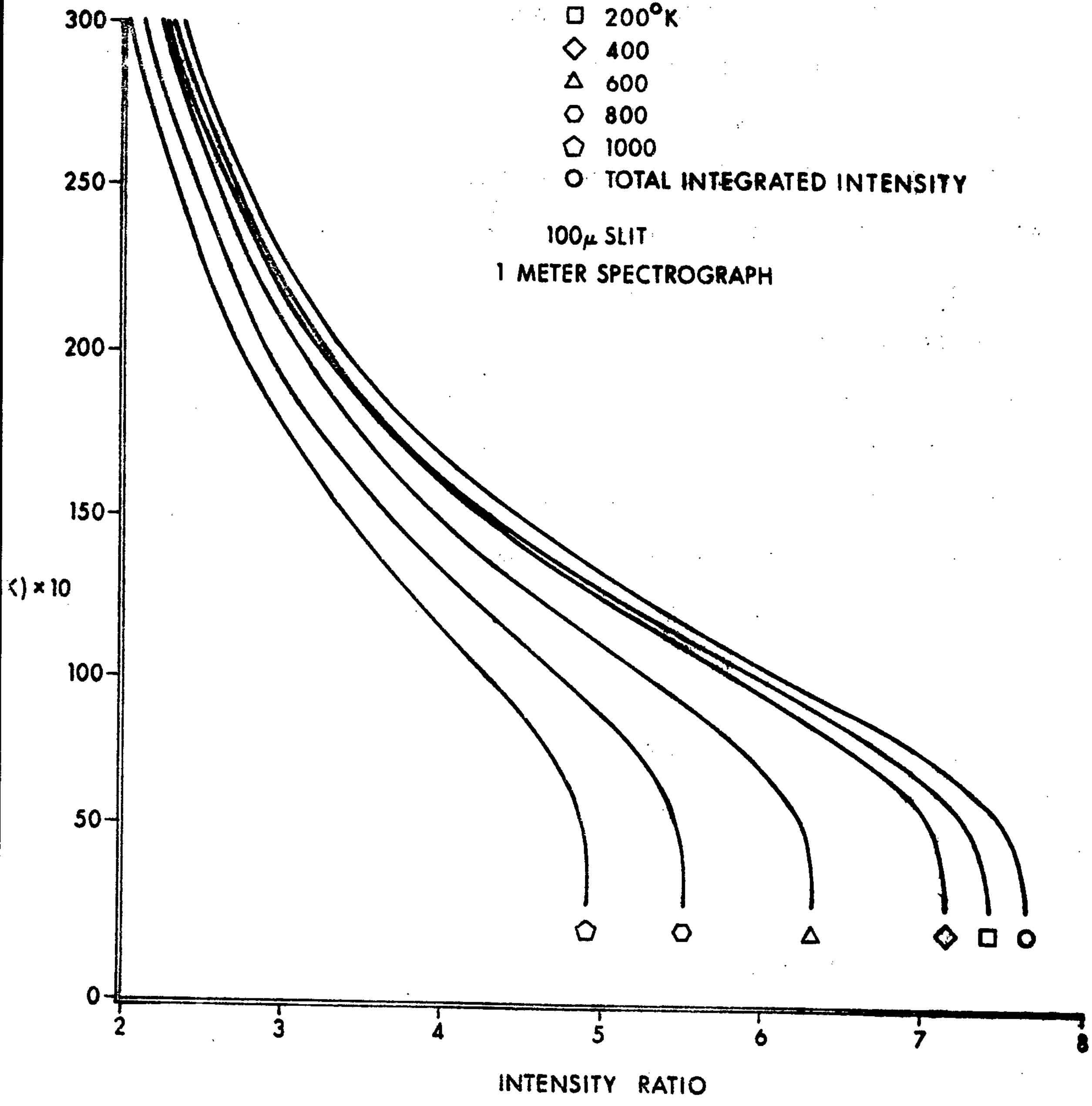

Fig. 1 VIBRATIONAL BAND RATIO FOR 01/12 BANDS

temperatures (less than about 800°K, the exact value depending on the rotational temperature of the gas) and at high vibrational temperatures (>2500°K). At both vibrational temperature extremes very small changes in intensity ratio correspond to large changes in the deduced value of the vibrational temperature. Thus small errors in the measured intensities can result in large errors in the value of the temperature.

Because the 2nd Positive System of Nitrogen, whose intensity under static conditions is found to increase with pressure, overlaps the R-branches of the 1st Negative System of N_2^+ (see Figure 2), it is impossible to use the total band intensities to determine the vibrational temperatures at the higher pressures of interest.[5] However, because the band heads of the (0,1) and (1,2) bands of the 1st Negative System are not overlapped by the 2nd Positive System, it is possible that these two band heads are usable for making the desired nitrogen vibrational temperature measurements.

Although these band heads are not overlapped, at higher pressure they are, however, not immune to the phenomena of quenching (the de-excitation, by collision with ambient molecules, of the electron beam produced 1st Negative System N_2^+ molecules before they radiate). Preferential quenching of either band head will result in wrongly determined intensity ratios that cannot be related to a vibrational temperature. The quenching problem can be potentially serious since pressure limits for rotational temperature measurements have been found to be quite low. Under static conditions, the rotational structure of the R-branch of the (0,0) band, which is the band most commonly used to make nitrogen rotational temperature measurements, corresponds to the correct Boltzmann distribu-

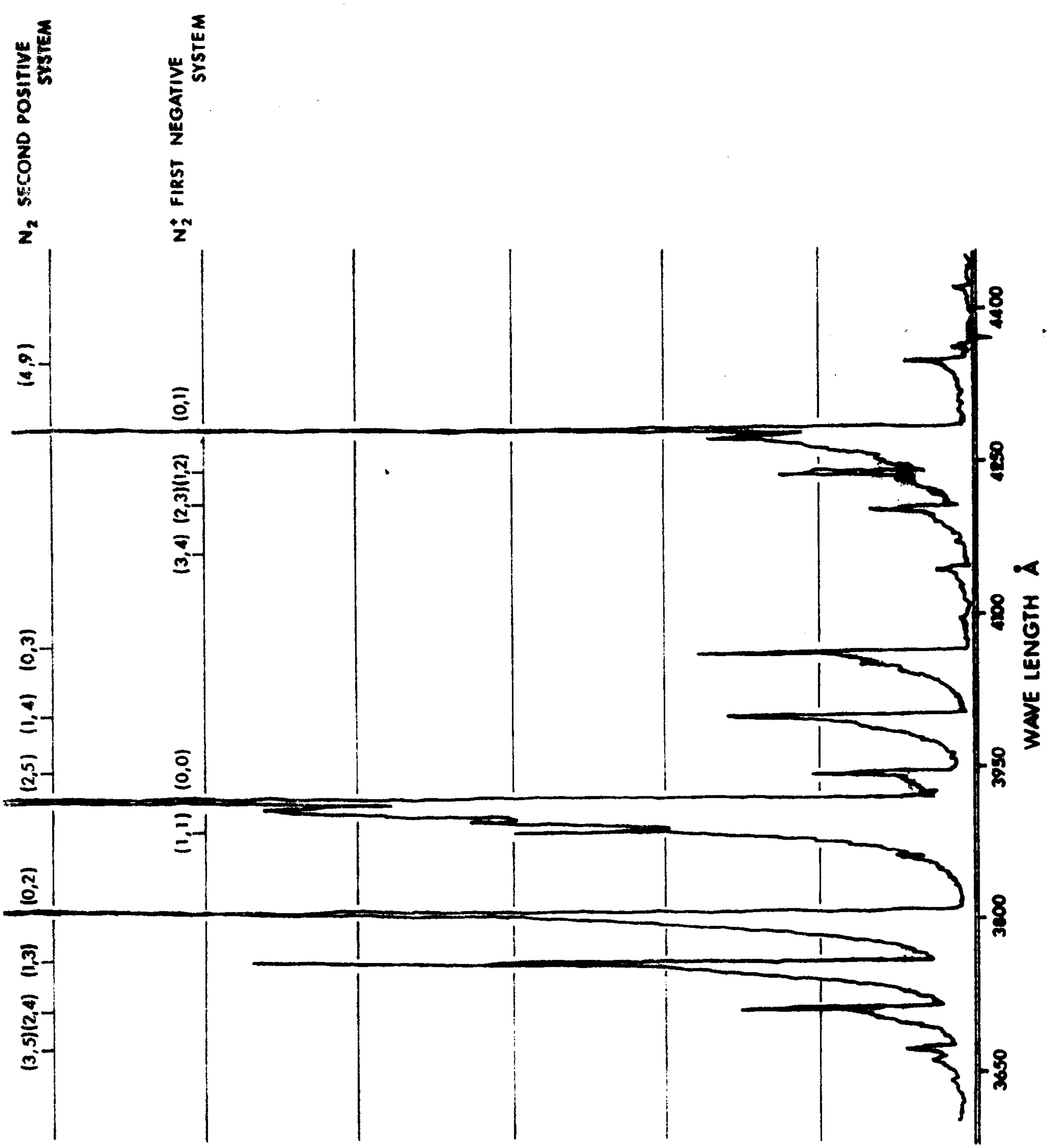

FIG 2 Band Interference between the 1st Negative System of N_2^+ and the 2nd Positive System of N_2

tion only up to pressures of 0.5 Torr. Thus in order to establish the usefulness of these band heads in making vibrational temperature measurements, the effects of quenching, as a function of pressure, must also be established.

SECTION IV

EXPERIMENTAL PROCEDURE

To take account of various instrument characteristics which remain constant from measurement to measurement, such as the efficiency of the optics and light path geometry, both of which affect the measured intensity ratios, the intensities of the two band heads at known conditions of temperature and pressure must be measured prior to each data run. This was done by measuring the intensities of the (0,1) and (1,2) band heads in room temperature static air, but at low pressure (less than 0.8 Torr), so that the afore mentioned quenching and overlapping problems were not encountered and the resulting spectrographic data could be validly interpreted.

During the runs, spectral scans of only the (0,1) and (1,2) band heads were obtained. (The run time was insufficient to obtain scans through the R-branches of both bands.) The resulting run data was then reduced in the following manner. Since the intensities of the band heads are proportional to their area, the areas were determined with a planimeter. Due to fluctuations in the values of the electron beam current during a scan, the band areas were normalized with respect to the beam current, thus eliminating any changes in intensity caused by changes in beam current. The resulting normalized areas of the (0,1) and (1,2) band heads were then ratioed and corrected with the calibration intensity ratios obtained before each run. The resulting corrected value of the intensity ratio was used to determine the vibrational temperature by relating it to the proper curves of figure 1.

No measurements of nitrogen rotational temperatures were made. The rotational temperature values used in the post shock region were calculated from oblique shock-wave theory.

SECTION V

APPARATUS

ELECTRON BEAM GENERATOR

The newly developed AFFDL high current electron beam generator was used for all tests. The generator and electromagnetic steering and focusing systems were placed inside the HTF test cabin while the associated power console and controls were located adjacent to the wind tunnel. The electron beam was projected downward within the test cabin. Electromagnetic steering enabled the beam to be deflected up to 40 degrees from the vertical. The beam current was monitored by measuring the voltage drop across a precision resistor, with the entire test cabin acting as a current collector, and was recorded on one channel of two, dual-pen recorders. The other channel recorded the electron beam induced spectral information which was obtained with two spectrometers (see below). Typical operating beam currents and voltages for all the measurements were 7ma and 30kV, respectively.

SPECTROSCOPIC EQUIPMENT

Two spectrometers, a Spex 1/2 meter with a 2400 l/mm grating and a 1 meter McPherson equipped with a 2160 l/mm grating, were used to monitor the free stream while the other collected data from the post-shock, high pressure region between the shock wave and the model. The exact portions of the flow, relative to the models, observed by the spectrometers was found by back-lighting from their exit-slits to the tunnel measuring stations. The location, length, and width of the resulting slit images was

maximized for optimal recording of the spectral information. Figure 3 shows a schematic of the optical set-up with respect to the wind tunnel.

FLAT PLATE MODEL

During the initial portion of the study, a thin flat plate, set at an 8 degree angle of attack to the free stream, was used to generate the shocked test gas. The free stream nitrogen vibrational temperature was monitored with the Spex 1/2 meter spectrometer which was equipped with 50μm entrance and exit slits. The entrance slit image at the free stream measuring station was 2 1/2 inches long and 1/16 inches wide. It was located above the flat plate, 7 3/4 inches from the leading edge (see figure 4). The bottom edge of the slit image was positioned 2 5/8 inches from the plate to assure that it was outside the region of shock wave influences. With respect to test cabin coordinates, the center of the slit image was located 1.5 inches above the tunnel centerline.

The higher pressure spectral information between the shock wave and the plate was recorded with the McPherson 1 meter spectrometer which was equipped with 200μm entrance and exit slits. The image of the entrance slit was positioned parallel to the surface of the flat plate. At the measuring station, the image size was 3/32 inches wide and was located 7/16 inch above the plate surface, approximately 10 3/4 inches down-stream from the leading edge. This location was chosen so that the observed flow would be outside the plate boundary layer but within the uniform post-shock region generated by the plate. With respect to tunnel coordinates, the shocked test gas was 1/2 inch below the tunnel center line and 17 inches downstream of the nozzle exit. In these flat plate tests the electron

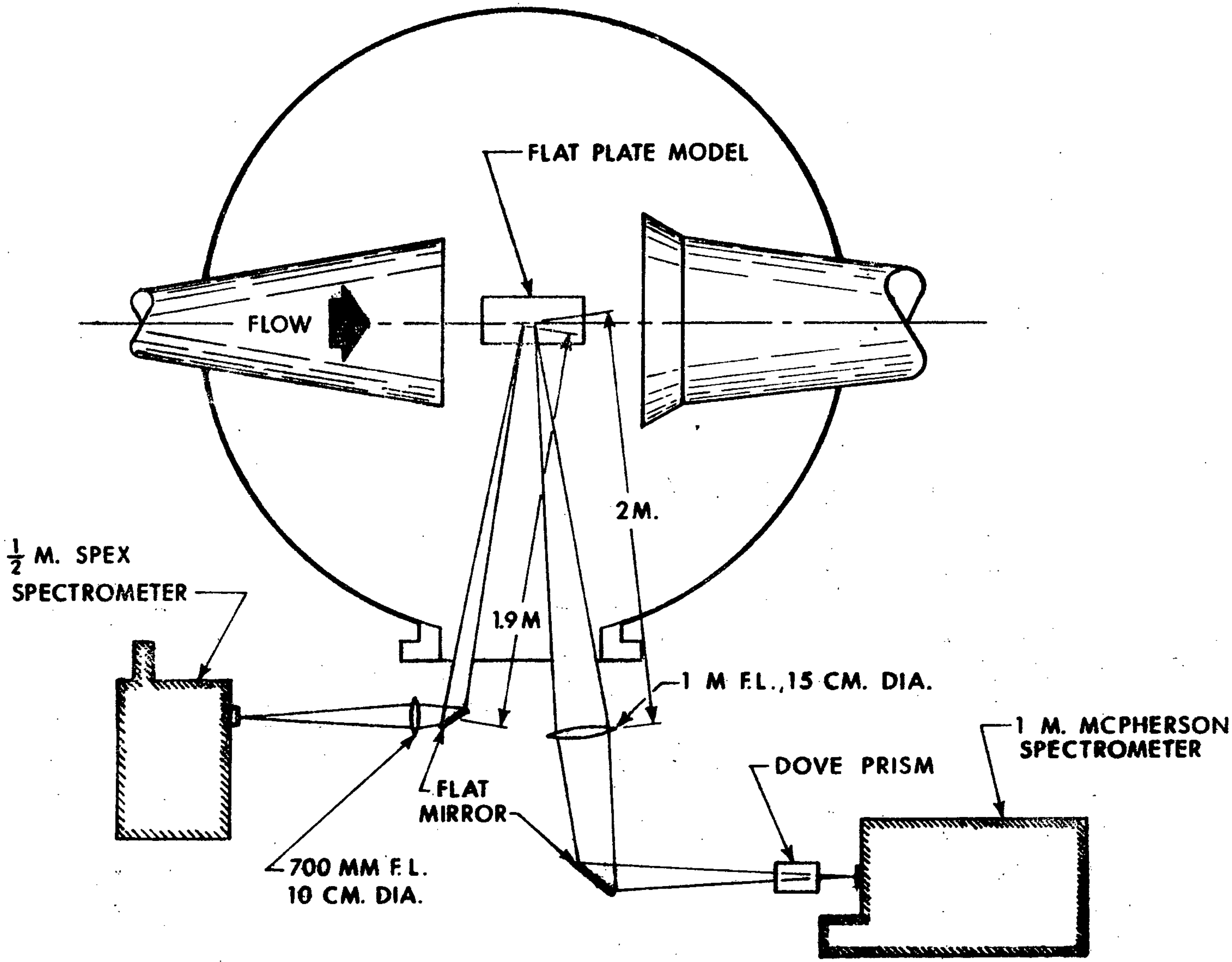

Fig. 3 OPTICAL LAYOUT OF TEST

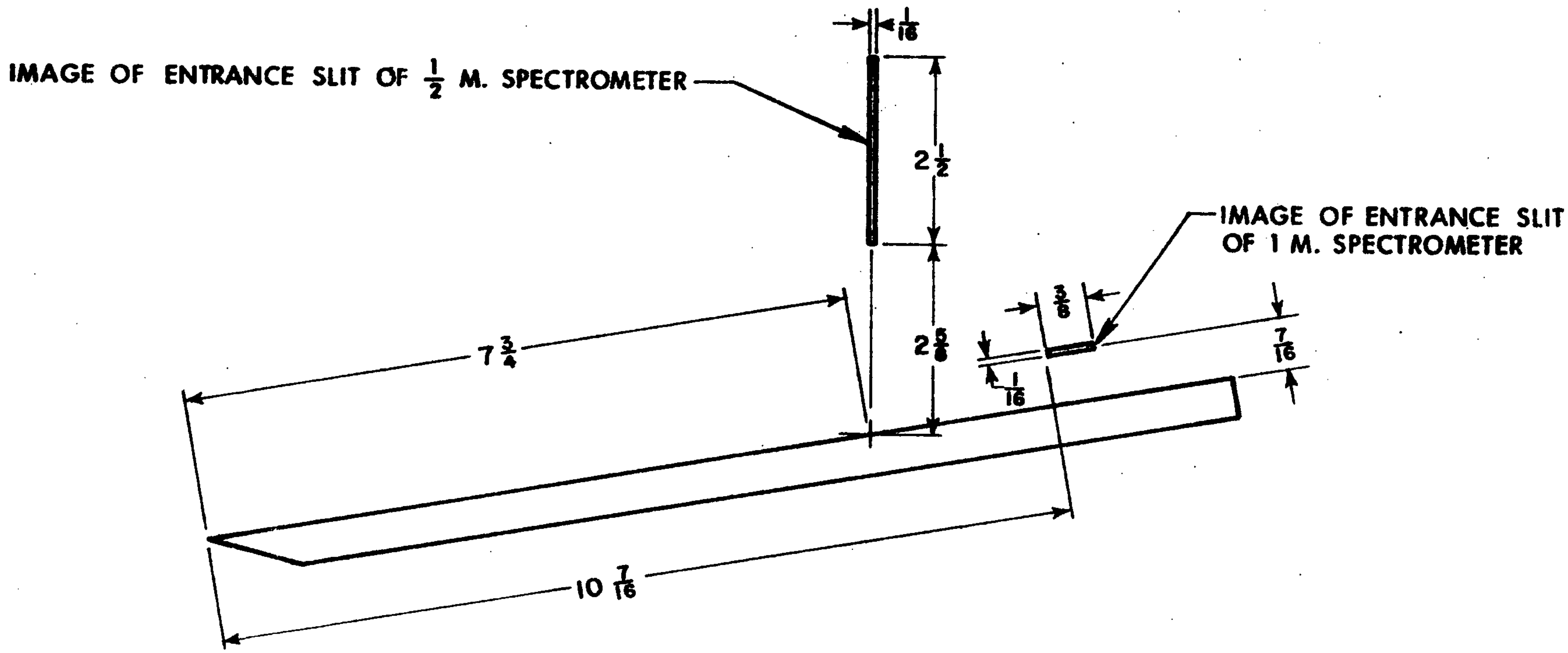

Fig. 4 IMAGES OF SPECTROMETER SLITS FOR FLAT PLATE TEST

beam passed through the centerline of the test cabin, 3 inches downstream of the nozzle exit.

CYLINDRICAL MODEL

After failing to obtain meaningful intensity ratio data with the flat plate due to reflection of electrons from the plate surface, it was replaced with a solid cylindrical aluminum model, 2 1/2 inches in diameter and approximately 6 inches long. This was done for two reasons: firstly, by aligning the beam in front of the model and parallel to the face, the production of secondary electrons by reflection would be minimized; and secondly, a high pressure could be immediately generated behind the bow shock.

The model was positioned so that the cylinder face was perpendicular to the flow. The region probed with the electron beam was located between the bow shock and cylindrical face. The Spex 1/2 meter spectrometer was used to make the measurements. Both the beam and the spectrometer slit images were aligned parallel to the front face of the cylinder, approximately 1/4 inch in front of the model. To make sure that only the uniform gas cap region was observed, the height of the spectrometer entrance slit was masked off, reducing the slit image length at the test gas to 2 inches. The resulting image was located entirely between the bow shock and the model face.

The free stream nitrogen vibrational temperature was monitored with the McPherson one meter spectrometer, with its entrance and exit slits set at 200μm. The slit image was aligned parallel to the tunnel centerline and was positioned to intersect the electron beam 2 inches above the model but outside the region of bow shock interference.

A few runs were also made with the McPherson 1 meter spectrometer observing the flow field in the shoulder region of the cylindrical mode. In this case the spectrometer slit image was located parallel to the model, approximately 1/4 inch above the cylinder.

SECTION VI

RESULTS

PRELIMINARY RUNS

The initial portion of the study consisted of calibration tests without any models in the flow to check-out the electron-beam generator and the spectrographic instrumentation and to become familiar with the HTF tunnel operational environment. This procedure was necessary since both the investigators and electronic technicians had little previous experience with the new high power electron-beam generator in the HTF facility.

Both during these pre-test investigations and during some of the actual runs with the models in the flow, electron beam nitrogen vibrational temperature measurements of the free stream were obtained. These measurements were used as a control to check the validity of the vibrational temperature measurements at the higher pressures and to theoretically predict the N_2 vibrational temperature in the shocked gas. Since the free stream flow was characterized by pressures and temperatures where the aforementioned problems of quenching or band overlapping do not occur, the obtained values for the nitrogen vibrational temperature would be an accurate standard. Typically the free stream static pressure was 0.5 Torr, the static temperature was under 100°K, and the nitrogen vibrational temperature was approximately 1000°K. In all these cases, the nitrogen vibrational temperatures were deduced by measuring the recorded areas of the (0,1) and (1,2) band heads. Due to the short run times available, and because of the previously mentioned problems associated with overlapping by the 2nd Positive System, rotational profiles of the P and R branches

of the (0,1) and (1,2) bands could not be obtained and thus their rotational structure was not investigated.

The free stream results from the preliminary runs and those made with models in the flow are summarized in Table I. It must be pointed out that both spectrometers were used to obtain this data. The Spex 1/2 meter spectrometer obtained the free stream data for the flat plate tests while the McPherson 1 meter spectrometer was used in the cylinder tests. Scatter in the data is mainly caused by electron beam current noise and fluctuations. As a result, some of the band head area measurements were very difficult to normalize with respect to the correct value of the current, especially in those cases where the current changed drastically in the middle of a band head scan. In other scans, the peak-to-peak electron beam noise was a significant percentage of the total value of the current. Because the response of the spectrographic and beam current electronics package are different, a one-to-one match up between intensity and beam current could not be made. Table I only includes data for those runs in which the electron beam noise or current fluctuations were not excessive.

For the 400 psi condition, the average free stream vibrational temperature was found to be approximately 990°K. The resulting average vibrational to reservoir temperature ratio, T_V/T_O, was then approximately .73. For the 100 psi condition, the single good measurement gave a T_V = 875°K and T_V/T_O= .75.

FLAT PLATE TESTS

Nitrogen vibrational temperature data were obtained in the post-shock region using the flat plate set at an 8 degree angle of attack.

TABLE I

FREE STREAM MEASUREMENTS

Run #	P_o psia	Int Ratio	T_o	T_V	T_V/T_o	Spectrograph
134	400	6.21	1528°K	1000°K	.6544	1/2m
135	400	6.20	1323°K	1000°K	.7558	1/2m
136	400	5.97	1292°K	1050°K	.8126	1/2m
136	400	5.71	1292°K	1125°K	.8707	1/2m
137	400	6.93	1409°K	800°K	.5678	1/2m
138	400	6.27	1372°K	970°K	.7071	1/2m
138	400	6.22	1372°K	990°K	.7217	1/2m
147	100	6.68	1162°K	875°K	.7532	1m

This small angle was chosen to keep the post-shock pressure in a regime where vibrational temperature measurements had already been made, i.e., under 5 Torr, to guarantee a high degree of confidence in the measured values. At this angle of attack the post-shock static pressure was approximately 3 Torr, the static temperature about 100°K and the vibrational temperature about 1000°K. For all cases, the measured area ratios of the (0,1) to (1,2) band heads were too high for the gas conditions observed, i.e., the nitrogen vibrational temperatures deduced from the areas were too low. Typically, vibrational temperatures below 800°K Kelvin were obtained, while the free stream vibrational temperature was on the order of 1000°K. Some of the values of the intensity ratios were so high that they were to the right of the intensity ratio curves of figure 1. Table II summarizes these results.

The most probable explanation for these anamolous results is excitation of the test gas by secondary electrons which are produced by reflection of the primary beam from the flat plate. We have observed the same effect of high intensity ratios in the laboratory, under static conditions at higher gas pressures. Another possible explanation originally advanced to explain the low vibrational temperature, but which was later abandoned, was too high a rate of nitrogen vibrational relaxation. The disquieting factor in all this was that wrong temperatures were measured at pressures where the technique had been shown to work. As a result, it was concluded that the experimental set-up was wrong and thus it was decided to abandon the flat plate model and try to generate the desired pressures with the solid cylinder.

TABLE II

FLAT PLATE RESULTS

Run	I_{nt} Ratio	T_v	P_o psia	T_o
142	7.70	?	400	1263°K
142	7.12	750°K	400	1263°K
141	8.14	?	400	1290°K
141	6.77	850°K	400	1290°K
141	8.76	?	400	1290°K
141	7.28	680°K	400	1290°K
140	10.81	?	400	1312°K

(The question marks in the T_v column refer to intensity ratio values which fell to the right of the curves in Figure 1)

CYLINDER TESTS

Having failed to obtain the proper data with the flat plate at low pressures, it was decided to go directly to a high pressure environment generated by the bow shock of a solid cylinder. To avoid secondary electron effects the electron beam was passed through the gas cap region between the bow shock and cylinder face. In the gas cap the expected vibrational temperature was ~1300°K and, because of the high pressure, the rotational temperature was expected to be approximately equal to this value. Such a high value for the rotational temperature has the immediate consequence that the (1,2) band head is overlapped by the high intensity rotational lines of the R-branch of the (0,1) band (see Figure 5). To be able to separate the (1,2) band head from the rotational lines of the (0,1) band, full scans of both bands would have been required. This, however, was not experimentally feasible in view of the short run times available and the long times needed to perform such spectrometer scans. The typical run times of 3 minutes were too short, being just sufficient to scan through both band heads. Thus the gas cap region could not be used to make the desired tests. An encouraging outcome of these tests was that the electron-beam had no problem penetrating the high pressure, 40mm gas inside the gas cap.

To obtain a lower value of the rotational temperature, measurements were then made in the shoulder region of the cylinder. Because the flow there is processed by an expansion fan, it would have a high vibrational temperature, and depending on the position down-stream from the corner, a low static pressure and temperature. However, there was no experimental or theoretical capability at hand to predict the values of the latter

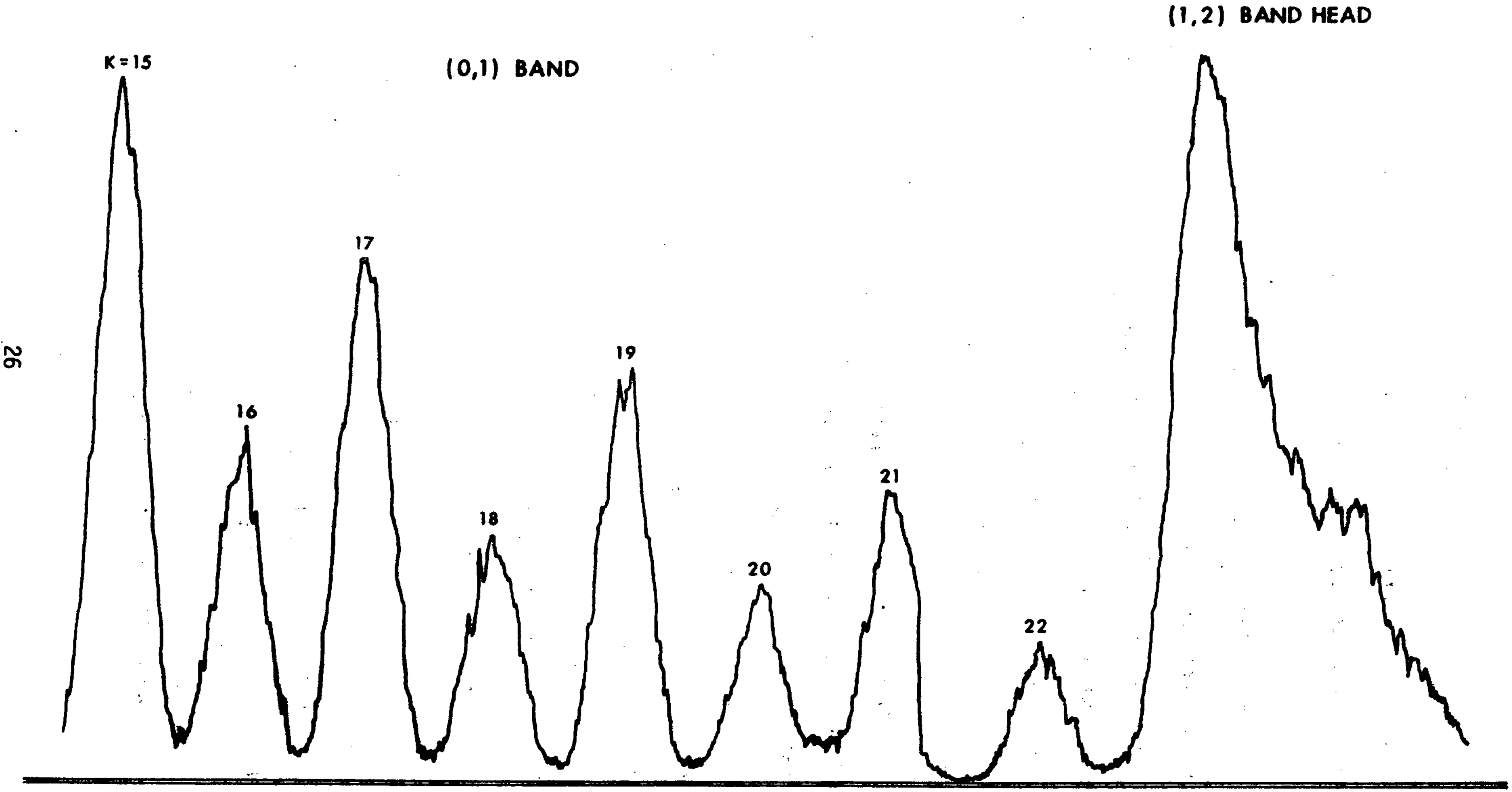

FIG. 5 Overlapping of (1,2) Band Head by Rotational Lines of (0,1) Band R-Branch

parameters as a function of distance along the cylinder, and thus the technique could not be used for calibration purposes. The spectral scan obtained from one run, set at an arbitrary location along the cylinder, still showed a high rotational temperature, with the higher number rotational lines of the (0,1) band overlapping the band head of the (1,2) band.

SECTION VII

FLOW VISUALIZATION

The electron beam technique has been shown to give fairly detailed flow visualization in flows of the type investigated in this study. As a result, for both models, flow visualization data was obtained in the form of color, 35mm slides. These clearly detail the shock wave regions probed by the beam for both models and show that the beam can pass through flows characterized by pressures as high as 40 Torr. This data is available from the authors upon request.

SECTION VIII

CONCLUSIONS

An unsuccesful attempt has been made to verify the validity of electron beam nitrogen vibrational temperatures at static pressures above 5 Torr. The cause of failure was the use of models to generate the desired pressures. For the flat plate tests, secondary electrons produced by reflection of the electron beam from the plate surface invalidated the molecular nitrogen excitation scheme used to derive a vibrational temperature. In the case of the cylinder tests, the resulting rotational temperatures were too high, causing serious overlapping of the bands used in the analysis. Measurements made in the shoulder region of the cylinder could be valid, if secondary electron production were negligible and if a theory were available to correctly predict the values of the gasdynamic parameters at the measurement point.

The ideal way to extend the validity of such measurements is to produce a test flow characterized by high vibrational temperature,low rotational temperature, and static pressures on the order of 40 Torr. This could be most easily done by using a high expansion nozzle. Thus, it is recommended that these tests be continued using the recently installed GDL nozzle array in the Laboratory's High Temperature Facility. This would provide a source of test gas whose parameters would be accurately defined and easily regulated. In addition, effects due to secondary electron excitation would be completely eliminated.

SECTION IX

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